Recent Developments in Laser Cutting of Metallic Materials

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Abstract

Laser cutting has become an extensively used method of material removal with cost effective solutions for complex manufacturing processes. Consequently, the process has become an area of intense research and development activity where researchers and industry experts are focusing on maximizing the productivity and reducing the cost while maintaining a high quality. Laser cutting, as the prevalent application of laser beam machining (LBM), offers a competitive advantage over conventional cutting processes in terms of material savings due to narrow kerf width, less heat affected zone and minimum distortions. The process offers high precision and good surface quality, with no tool wear and easy automation. The current paper aims to present an overview on the recent research on laser cutting of metallic materials, in terms of process monitoring and control as well as modeling and optimization, and to summarize the past five years of research on the topic.

Keywords
Heat affected zone, kerf width, laser cutting, surface roughness.

1. Introduction

Laser beam machining (LBM), with capabilities to cut, trim, drill holes and weld in a wide range of materials have become the most widely used thermal energy process. The process is applicable from a macro-machining scale to micro and nano-machining. With a growing automotive industry and increase demand for precision and accuracy in aerospace, electrical and electronics sector, laser cutting, have gain advantage over traditional cutting processes such as oxy-fuel cutting, plasma cutting, sawing and punching. Laser cutting is a thermal process without contact, capable to produce accurate profiles with high cutting rates in a variety of materials, and to easily adjust to meet the requirements of new products., For more than two decades researchers embarked on to study closely the interaction between the process parameters and to optimize the processes for better quality and faster production. In laser cutting, research have been conducted around the influence of the process parameters on the quality of the laser cut (Pavlica, 2015) The criteria for evaluating the quality of the cut surface as well as the dimensional tolerance is given in standard EN ISO 9013:2000. Evaluation of the quality of the cut is based on surface of the cut, geometry of the cut, burr formation and the characteristics of material in the cut zone. The geometry of the cut evaluation is based on kerf profile (taper) and kerf width, perpendicularity and slant tolerance.
Most cut quality characteristics evaluated in previous research are the cut surface roughness, the kerf width and the HAZ (heat affected zone), while the most input parameters considered are the laser power, cutting speed and gas pressure (Radanovic, 2011)

The current paper aims to present an overview on the recent research on laser cutting of metallic materials, in terms of process monitoring and control as well as modeling and optimization, hence to summarize past few years of research on the topic. The metallic materials under consideration are those with commercial and industrial importance and include ferrous, non-ferrous and metal alloys.

2. Laser beam cutting

Laser cutting is the prevalent application of lasers in metal processing due to its competitive advantage over conventional cutting processes in terms of material savings, high precision and good surface quality, no tool wear and easy automation. The focused laser beam allows for a tool free cut with great accuracy, narrow kerf and minimal heat affected area.
Laser cutting is a thermal process whereas an intense energy laser beam is focused in a very localized spot on the surface of the material to be cut. The energy is absorbed by the material and converted into heat such that the material melts or vaporize throughout its thickness, while assist gas is ejecting molten material away from the cut. As laser cutting is having a large number of parameters with nonlinear and complex interaction between them, efforts are constantly made to understand the process and model it for best cut quality and faster cutting speed.

2.1 Methods of metal laser cutting

Depending on the amount of energy supplied and the type of assist gas used there are three methods to cut metals, namely: fusion cutting, flame cutting and sublimation cutting.

Laser fusion cutting requires enough power to melt the material throughout its thickness. It uses reaction inhibiting Nitrogen or Argon as the assist gas. The gas is blown coaxially with the laser beam at pressures between 2 and 20 bar (Pavlica, 2015) and has the role of expelling the molten metal from the cutting zone, cooling the material and shield the cut preventing edges from oxidation.

Laser flame cutting or laser burn cutting uses oxygen as the cutting gas. The gas is blown into the cutting joint at pressures up to 6 bar (Pavlica, 2015), and reacts chemically with the material being cut, with release of large amounts of energy, considerably increasing the input energy. However, due to chemical reaction between O_2 and the material, will result in an oxide layer on the cutting edge that influences the cut quality. This method is used in high speed cutting of thick metal sheet where a good cut quality is not a requirement.

Laser sublimation cutting or vaporization cutting uses nitrogen, argon or helium as the process gas at low pressures of 1 to 3 bar. The gas serves only to shield the cut. The method involves vaporization of the material with as little melting as possible, therefore requires high laser power and it is slower but produces high quality cuts. The method is not commonly used in sheet metal fabrication.

2.2 Laser systems

All laser systems have three main parts: a pump source, a gain medium and a resonant system. The pump source may be electrical discharge, flash or arc lamps, or chemical reactions. The gain medium, where suitable excitation and population inversion occurs, may be liquid, solid or gaseous. The gain medium is contained in a chamber called cavity. At each end of the cavity there is a mirror, one is a partially reflective and the other totally reflective mirror, Figure.3. These mirrors form the optical resonator of the laser system. The output beam is delivered to the workpiece as a small spot of high energy after passing through a focusing lens.

Laser systems used for macro-machining are in general continuous-wave with laser beam power of up to several kW, while for micro-machining, pulsed beams systems with average power below one kW are used.
For cutting metallic materials the most common industrial laser machines used are CO_2 and NdYAG and fiber. The CO_2 laser, although it is one of the earliest that have been developed, it is currently the highest power continuous wave laser available. The gain medium is a mixture of gases (CO_2, Nitrogen, Helium and in small percent, hydrogen and/or xenon) that is either water or air cooled. It is electrically pumped and radiates at 10.6 μm wavelength.

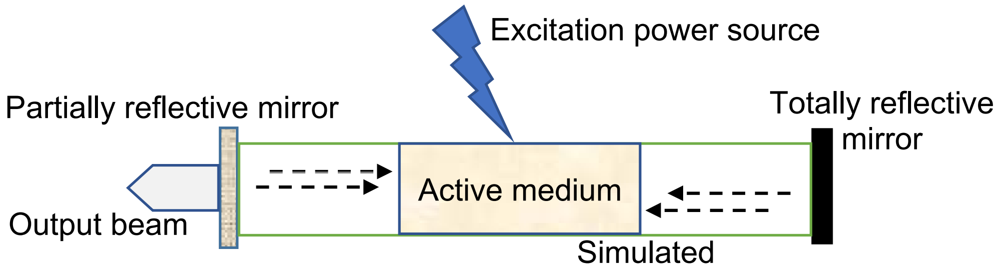

Figure 1. Diagram of main parts of any laser system

The gain medium in Nd:YAG laser is neodymium-doped yttrium aluminium garnet and the energy source is supplied by a bank of diodes or flash lamps. The output light beam is then collimated and focused by a lens on the material to be cut. The light is produced far more efficiently and is delivered in a much simpler system than the CO_2 laser. This optically pumped solid state laser that works at a 1.06 µm wavelength allows cutting of materials with higher reflectivity. The fibre laser working principle is similar with NdYag laser except that the gain medium is an optical fibre doped with rare elements like ytterbium, erbium, neodymium, etc.
Factors to be considered when choosing the appropriate laser system are the type of material to be cut, the thickness of the material and the reflectivity/absorptivity of it, the accuracy required, edge quality and number of components.

2.3 Laser cutting parameters

Laser cutting is a complex process governed by a multitude of factors with difficult to predict interaction. The parameters of laser cutting process can be classified as system parameters, the workpiece parameters and process parameters as illustrated in Figure 2.

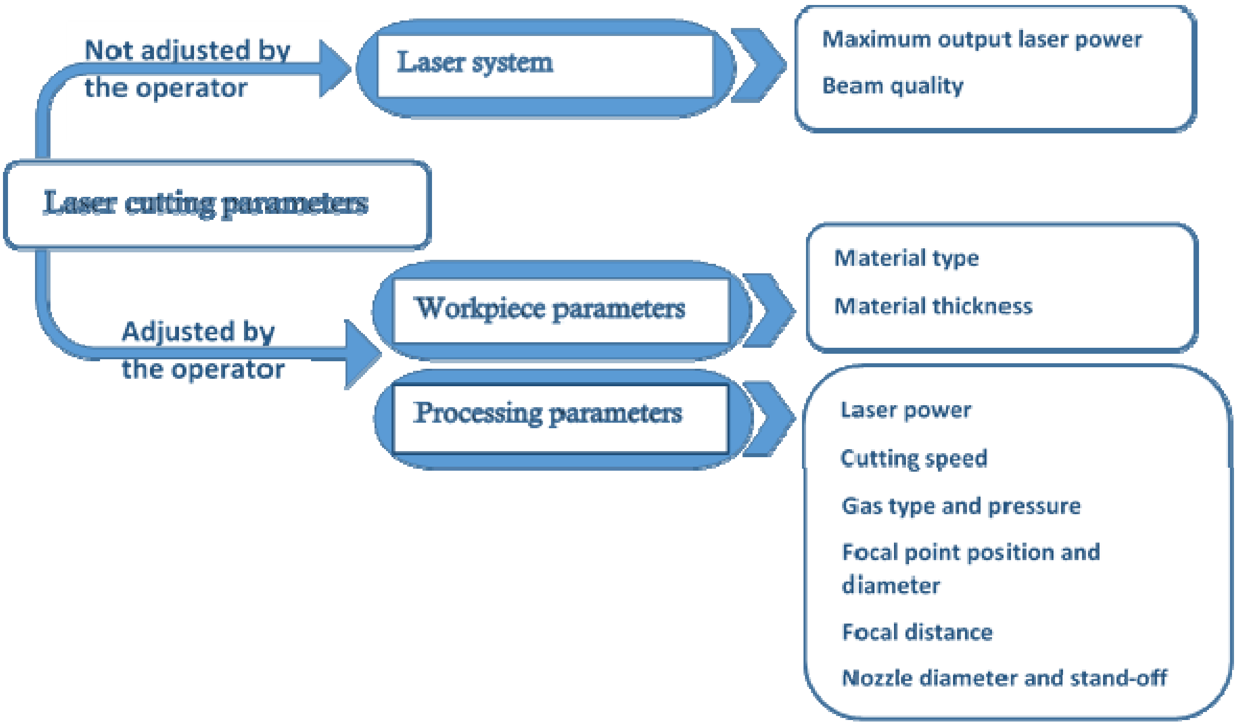

Figure 2. Laser cutting parameters

2.3.1 Workpiece parameters

Metals are characterized by high melting point, thermal conductivity and optical reflectivity. When referring to metallic materials the ones with lower reflectivity and thermal conductivity are most suitable for processing with laser. Both CO_2 and Nd:YAG laser machines have excellent capabilities for cutting the most common material used in manufacturing industries which is steel in all variants: mild steel, stainless steel, tool steel or alloy steel. Aluminium, titanium and nickel-based alloys, that are increasingly used in the aircraft industry, are also fairly good processed by both laser systems. However, materials that are highly reflective like copper and its alloys, gold and silver, are difficult to cut. Most used material type in recent research is mild steel and stainless steel, Fig 2. Varkey (2014) and Solanki (2016) conducted investigation on Ti6AlV4 and Ti grade II respectively, while Parthiban (2015) and Leonea (2015) used 6061-T6 aluminium alloy. Tungseten alloy was used by Hajdarevic (2017) and Klancnik (2014), and Ni-based alloy was used by Sharma (2015).

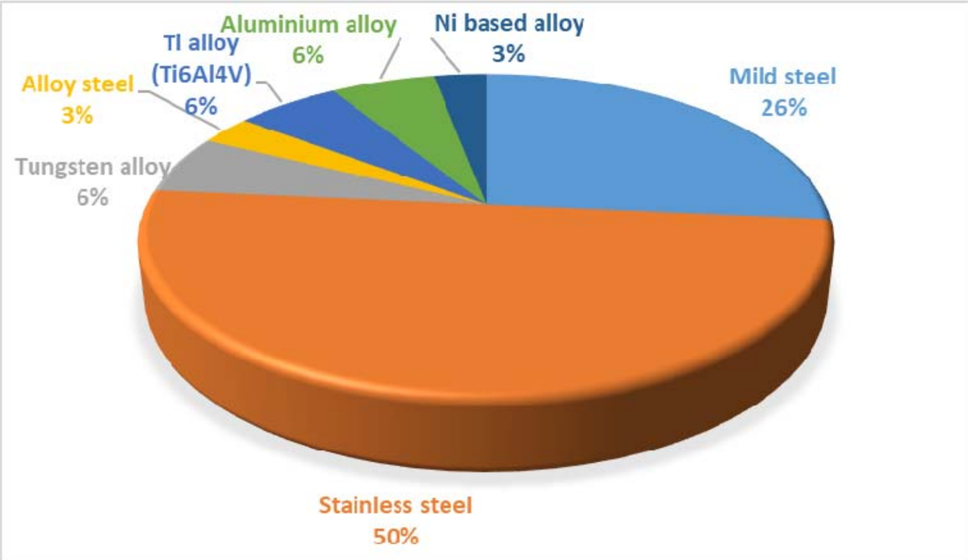

Figure 3. Materials investigated in recent research

The thickness of the piece to be cut influences the power required to melt or vaporize the material and the cutting speed. For thicker materials, slower cutting speed and higher power is needed. Orishich (2016) investigated the utmost thickness of a low carbon steel sheet using fibre and CO_2 laser and O_2 as the assist gas. He found a maximum thickness of 40-50 mm that can be cut with CO_2 laser with a good cut quality. However, the method of determination of the maximum thickness could not be applied to fibre laser cutting. The thickness of the sheet metal used in recent research varies between 1 and 10 mm. Tamura (2015) studied the cutting of thick steel plates and simulated steel components using 30 kW high power fibre laser. He successfully cut carbon steel and stainless steel up to a thickness of 300 mm proofing that the process can be used in decommissioning of nuclear plants.

2.3.2 Process parameters

The laser power, known also as the heat input is dependent of the type of material to be cut, its thickness and the desired cutting rate. Materials like stainless steel and aluminium will require about 1000 W of heat input for cutting 1 mm thick sheet while mild steel and titanium of the same thickness, around 400 W of heat input.

Laser cutting is most efficient process in terms of its feed rate. Maximum cutting speed can be used when matched with the appropriate level of power and assist gas pressure to successfully cut a given thickness with good cut quality. Golyshev (2015) studied the maximum cutting speed as a result of the laser beam polarisation. He found that the maximal cutting speed is reached when the field vector coincides with the cutting direction. Jarosz (2016) investigated the effect of the cutting speed on surface quality and HAZ when cutting AISI 316L of 10 mm thick with CO_2 laser using nitrogen as assist gas. He found that cutting speed is influencing the width of HAZ and the presence of dross and burnt material. As the cutting speed is decreased from a maximum recommended value, the width of

HAZ was observed to increase and at 50% of the maximum recommended speed, the lower part of the cut becomes visibly damaged.

Typically, the assist gas used in laser cutting may be an inert gas such as nitrogen, argon and helium, or a reactive gas such as oxygen. The main role of the assist gas is to aid in the ejection of the molten metal from the cut zone. The pressure of the assist gas has an influence on the dross and striation formation on the cut surface. Stainless steel and Ni-based alloys are commonly cut with nitrogen as assist gas, whereas for titanium alloy argon is the choice. The other function of the inert gas is to provide cooling of the cut edge and help reduce the HAZ. Oxygen is generally used for cutting mild steel if the cut quality is not important. When using oxygen as an assist gas, this reacts with the constituents of the steel resulting in release of energy that adds to the energy provided by the laser beam. The process will result in an oxide layer that may need removal. Chekic (2015) conducted an investigation of the cut quality of two high alloy steel using oxygen and nitrogen as assist. He concluded that when higher productivity is required, oxygen assist gas is suggested but for better cut quality the nitrogen assist gas is recommended. Klancnik (2014) also used …

Focal point and diameter are in fact the minimum diameter beam spot where the laser beam is focused after being passed through a focusing lens. This focal point has the highest power density and can be positioned above the surface of the material to be cut, on the surface, or below it somewhere along the thickness of the material. The focal length is the distance between the focusing lens and the focal spot with minimum diameter. Longer focal lengths are required for cutting thick sections, while for thin sections a lens with shorter focal length is suggested (Eltawahni 2016).

Laser beam diameter have been investigated by Miraoui (2016) along with laser power and cutting speed. He reports that the laser beam diameter is the input parameter with the least influence on the HAZ however, it shows to have the most influence, together with laser power, on the melting zone (MZ). The depth of the melting zone increases with the laser beam diameter.

The nozzle has the role to guide the assist gas in a coaxial fashion with the laser beam, and their good alignment plays a role in the cut quality. When misaligned, the gas may flow on the surface of the workpiece, creating undesirable burning or spatter of the molten metal resulting in a poor-quality cut. The stand-off distance is the distance between the nozzle and the top surface of workpiece and is usually between 0.5 to 1.5 mm to minimize turbulence (Eltawahni 2016). There are few standard nozzles designs used in industry like parallel, conical, convergent, convergent-divergent nozzle, etc. Marimuthu (2017) designed supersonic laser cutting nozzle assembly that can deliver oxygen at high velocity and mass flow rate. The evaluation of the developed nozzle revealed good gas flow characteristics inside and outside the nozzle, uniformity in pressure and no shock waves. The nozzle was used to successfully cut 50 mm carbon steel, with 1kW CO_2 laser. That is an effective way to cut thick steel using a low-power laser source.

2.3.3 Laser cutting process performance

The performance of laser cutting process is determined by the cut quality features. These features, as presented in Figure 4., are specific to the geometry and surface of the cut, mechanical and metallurgical characteristics of the cut.

In the current research, the process performance have been mostly evaluated in terms of average surface roughness Ra and HAZ followed by kerf width and kerf tapper. Other output parameters studied are microhardness (Chekic, 2015: Velayutham; 2018, Miraoui, 2016). Li (2018) investigated striation formation and developed a strategy to suppress striations based on the power modulation. Experimental work of Patel (2016) showed that the material removal rate is maximum when using maximum laser power, cutting speed and gas presure. Pocorni (2015) employed a high speed camera to observe the melt flow while Miraoui (2016) measured and analyzed the depth of the melt zone and Librera (2014) performed a 3D topography of the cut edge for two types of laser cutting machines.

3. Modeling and optimization of the laser cutting process

The real physical process in laser cutting is characterized by a large number of parameters and research is continuously seeking to optimize the process for improvement of the quality and efficiency characteristics. The approaches used to determine the optimal laser cutting process conditions for a given applications have been identified by Madic (2017) as: trial and error method, Taguchi method, continual optimization and discreet optimization.

The trial and error approach it is based on the experience gained by working with the process and, although is a common approach in the industry due to its simplicity, the possibility of finding the optimal parameter settings is minimal, hence the machine is not used optimally.

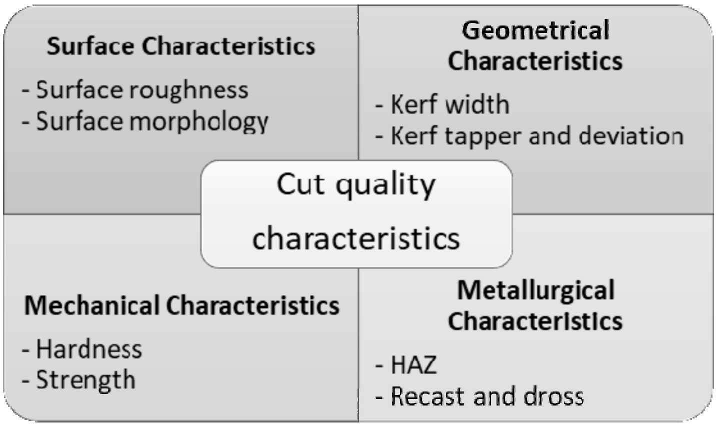

Figure 4. Cut quality characteristics

Taguchi method is a very popular as this method does not require development of a mathematical model and delivers a near optimal process conditions. It is powerful and simple to implement however does not allow for multiple objectives optimization.
Continual optimization is the approach where an empirical model is developed, in order to create objective functions that relates the input and output parameters and further optimize the process by using an optimization method. The integration of empirical models and optimization methods results in a continuous single or multi-optimization of laser cutting conditions. The method, although providing the best solution, is time consuming and computationally expensive and its application requires high level of knowledge
Multi criteria decision making (MCDM) is another method of determining the laser cutting process conditions that uses the performance characteristics as the criteria on which the particular pre-known cutting conditions, or alternatives, are assessed. Although has few relatively simple mathematical models that assesses and ranks the alternatives the method is not common.

Design of experiments known as DOE is the name given to several techniques used to guide the choice of the experiments to be performed in an efficient way. Any DOE approach must incorporate the three features namely replication, randomization and blocking as to satisfy the basic principles of statistical methods. Some DOE techniques are: full factorial, fractional factorial, Taguchi, RSM (Response Surface Methodology) with two approaches, CCD (Central Composite Design) and BBD (Box-Behnken Design), etc.

Not all papers investigated used a DOE method or presented an optimization technique.
Taguchi orthogonal array was the most employed DOE (Madic 2014, 2015, 2017; Miraoui 2016; Panu 2014; Gadallah 2015), followed by full factorial design (Nassar 2016; Patel 2016; Leonea 2015). Parthiban (2015) used RSM's Box-Behnken design of experiments techniques to develop linear, 2FI and quadratic models that have been compared with the experimental data. Cekic (2015) used a multiple linear regression analysis to derive sufficient and reliable mathematical equations that defines the effects of relevant process parameters on the cut quality.

In terms of modeling and optimization techniques, Madic (2014) used a hidden single layer ANN (Artificial Neural Networks) trained with Levenberg-Marquardt algorithm, and obtained the correlations between cut quality characteristics and material removal rate. Madic (2015) in addition to ANN modeling, used Monte Carlo method to optimize the laser cutting parameter settings for minimum kerf tapper angle. Another approach used by Madic (2017) was the Preference Index Method and he found that the method cannot be effective in situations where there exist a large number of alternatives which have attribute values (performances) very close to preferred. Varkey (2014) developed second order regression models for kerf taper and surface roughness that have been used as objective functions in GA (Genetic algorithm) based multi-objective optimization of these quality characteristics. Klancnik (2014) developed back-propagation artificial neural network (BP- ANN) model for the analysis and prediction of surface roughness and kerf width cut quality and compared the predicted results with the experimental data. The developed method is especially useful for rare or unknown materials, where the prediction of cut quality based on the input process parameter can be made, before actual machining, to find the parameters that will result in sufficient quality. Chaudhary (2014) developed a software CATFMO (Computer Aided Taguchi-Fuzzi Multi-Optimization) for simultaneous optimization of multiple quality characteristics in laser cutting process. The software have been used for simultaneous optimization of kerf width, surface roughness and HAZ for difficult to cut Aluminium alloy and found suitable when compared with published experimental data. Parthiban (2014) employed the RSM statistical model coupled wit GA for the optimization of cutting parameters. Sharma (2015) obtained preferred laser cutting parameters by using GRA (Gray Relational Analysis) coupled with EM (Entropy Measurement) method. The EM was employed to compute the weights corresponding to each quality characteristic for finding the grey relational grade. The result was a reduction in kerf deviation by 30% from that obtained with Taguchi L27 OA. Velayutham (2018) used also Taguchi-entropy weighted-based grey relational analysis (GRA) approach where the entropy method is used to measure the weight to each response characteristics.

4. Conclusions

The paper presents the basic functioning of laser machine, the two main laser systems used in sheet laser cutting and the process parameters involved in laser cutting. In studying the process, majority of the research used for modelling process parameters such as laser power, cutting speed, gas pressure, and focal position while the gas type and nozzle distance have not been considered. Regarding the workpiece parameters, few papers explored different thicknesses of the same material or different types of material. Some research gave consideration to beam characteristics like beam polarization, diameter, pulse width and frequency. Apart from the usual output parameters regarding the cut quality such as surface roughness, HAZ, kerf width and tapper, other mechanical and metallurgical cut qualities such as the microhardness, the melt zone and melt flow have been observed.

The results of this study show that efforts to better model and optimize the laser beam cutting process are continuing. Although various theoretical and experimental models were used to describe the performance of laser cutting process, Taguchi method remains the preferred DoE method. The application in AI techniques like GA, Fuzzy logic, ANN, etc, have also been investigated with some interesting hybrid approaches.

As the interaction of the process parameters and their influence on the cut quality have been extensively studied for mild and stainless steel there is much scope in the further study of Ti and Al alloys. As the thickness of the material in the examined research was between 1 and 10 mm, greater thicknesses still needs investigation. For the validation of the process optimization with hybrid techniques, further research is recommended.

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